ON THE PLASMA TURBULENCE IN THE JOVIAN MAGNETOSHEATH

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Abstract

A new possibility to investigate the inhomogeneous structure of the transition region between Solar wind and Jupiter's magnetosphere is studied theoretically and tested experimentally. This possibility is based on the existence of compact radio sources inside the Jovian magnetosphere. It is shown both theoretically and experimentally that the characteristic scintillation frequency for scattering on interplanetary irregularities becomes extremely low in the periods of Sun–Earth–Jupiter opposition (Solar elongation about 180°) allowing detection of scattering on magnetosheath inhomogeneities that is masked in other periods by interplanetary scintillations. Scattering on the irregularities of Jupiter's transition region was quite likely observed with an upper limit of scintillation index estimated as $3 \cdot 10^{-3}$ that corresponded to relative electron density fluctuations of about 1% at scales of about 1000 km.

1 Introduction

Decametric radio emission of Jupiter (DAM) has been observed for many years using ground–based and recently space borne instruments (see, for example, Physics of the Jovian magnetosphere, [1983] and references therein). Extensive investigations of DAM and its physical origin resulted in essential progress in understanding this phenomenon. In particular, it is well known that DAM sources are associated with fast electron flows in the Jovian magnetosphere propagating along magnetic field lines. The DAM frequency is determined by the local cyclotron frequency of electrons. For any constant frequency the DAM source spatial scale is rather small determined by the magnetic field strength gradient along the magnetic field and by the transverse scale of fast electron flows. Temporal variations of DAM are weak on the time scales of several seconds. The existence of a small scale quasi–continuous decametric radio source inside the Jovian magnetosphere

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provides a possibility to study turbulence in the transition region between Jupiter's magnetosphere and Solar wind using observations of DAM scattering off large scale (compared to wavelength) plasma irregularities in this region.

Investigations of such kind were carried out for the transition region between Earth's magnetosphere and Solar wind [Tokarev et al., 2000]. The SURA heating facility operated in the long wave part of the decametric band and was used as a compact radio source inside Earth's magnetosphere. Space borne RAD–2 WAVES instrument of WIND spacecraft was used to receive the SURA radiation. Moving along its orbit, the spacecraft intersected the transition region, and changes in the scintillation spectra of SURA radiation were studied. An appearance of a high frequency (few Hertz) component of scintillation spectra was found in addition to low frequency ionospheric scintillations when the spacecraft was outside Earth's magnetosphere. This feature is found to be caused by scattering off large scale plasma irregularities in the transition region between the Earth's magnetosphere and the Solar wind.

The difference for ground–based observations of Jupiter's radio emission is in the wave propagation through the thick layer of the interplanetary medium. Interplanetary scattering (IPS), negligible in case of the Earth, would produce a substantial contribution to the DAM scintillation spectra. Generally, IPS affects the same frequency range of scintillation spectra as expected for the Jovian transition region, but it is much stronger. Fortunately, there is a case when the characteristic frequencies of IPS become very small, even below ionospheric ones, namely, the case of Sun–Earth–Jupiter opposition when DAM propagates to the Earth almost along the Solar wind direction.

2 Theoretical background

To reach the Earth the DAM passes through three media filled with inhomogeneities with different properties related to their contribution to scintillation spectrum. There are transition regions between the Jovian magnetosphere and the Solar wind, the interplanetary medium, and the Earth's ionosphere. Both ionospheric scintillations and scintillations caused by IPS were extensively studied, and scintillations due to scattering off plasma irregularities in the Jupiter's transition region are subject to study.

Interplanetary medium: Due to the decreasing of the Solar wind electron density (as square distance from the Sun) outside Earth's orbit, effective IPS of DAM occurs near the Earth in the layer of about $L_2 = 0.4$ AU (astronomical unit) thickness. The electron density in this layer has a typical value of $N_2 \approx 7$ cm^{-3} [Yakovlev, 1998; Gershman et al., 1984]. The outer scale of the Solar wind plasma turbulence is about $\ell_2 \approx 3 \cdot 10^5$–$3 \cdot 10^6$ km, and the relative electron density fluctuations can be estimated as $\sqrt{\langle \Delta N^2 \rangle / N^2} \approx 0.1$–$1$ [Yakovlev, 1998]. Using the values of parameters above one can estimate the mean square of the phase fluctuations of a radio wave propagated through this layer as $\langle s_2^2 \rangle = (k_0^2/2)(\omega_{pe}/\omega)^4(\langle \Delta N^2 \rangle / N^2)\ell_2 L_2$ where ω is wave frequency and $k_0 = \omega/c$–its free space wave number. For a radio wave of 10 MHz frequency $\langle s_2^2 \rangle \approx 10^5$–$10^8$. The characteristic scintillation frequency can be estimated as $\nu_2 = (V_2/\ell_2)\sqrt{\langle s_2^2 \rangle} \sin\theta \approx (0.3$–$2) \sin\theta$ Hz. Here V_2 is a mean value of the Solar wind velocity at the Earth's orbit distance (value of

450 km/s was used for the estimation above [Yakovlev, 1998; Gershman et al., 1984]), and θ is the angle between the radio wave propagation direction and the Solar wind velocity. Far from opposition the characteristic frequency ν_2 is of the order of 1 Hz, but in case of $\theta < 10^\circ$, close to opposition, ν_2 becomes essentially smaller with $\nu_2 \approx$ (0.03–0.2) Hz. The scintillation spectrum of IPS dramatically decreases (by Gaussian law) at frequencies above ν_2 [Alimov et al., 1997].

Earth's ionosphere: Let us consider a case of nighttime ionosphere under quiet geophysical conditions. In this case the effective thickness of the scattering layer can be estimated as $L_3 \approx 50$ km, the outer scale of ionospheric turbulence as $\ell_3 \approx 30$ km, the mean electron density as $N_3 \approx 10^5$ cm^{-3}, and $\sqrt{\langle \Delta N^2 \rangle / N^2} \approx 3 \cdot 10^{-2}$ [Alimov et al., 1997; Gershman et al., 1984]. Using the values above one can estimate for a radio wave of 10 MHz frequency a mean square of phase fluctuations of $\langle s_3^2 \rangle \approx 10^2$ and a characteristic frequency of $\nu_3 = (V_d/\ell_3)\sqrt{\langle s_3^2 \rangle} \approx 0.1$ Hz, and for a typical drift velocity of ionospheric irregularities $V_d \approx 300$ m/s [Gershman et al.,1984]. The decreasing of the ionospheric scintillation spectrum at higher frequencies is expected to be described by a power law due to a moderate value of $\langle s_3 \rangle$ [Booker and Majidiahi, 1981].

Jovian transition region: This is a region to be studied using the proposed technique. Nevertheless, some assumptions of the expected effects can be taken into account. First of all, it is expected that the mean square phase fluctuations should be weak, $\langle s_1^2 \rangle \ll 1$. The characteristic scintillation frequency can be estimated as $\nu_1 = (V_J/\ell_1) \approx$ (0.5–1) Hz. Here V_J is the Solar wind velocity relative to the emission source in the Jupiter's magnetosphere, which typical value is 300–600 km/s due to the fast rotation of the magnetosphere. The Fresnel scale of the plasma irregularities in the transition region between the Jovian magnetosphere and the Solar wind is equal to $\ell_1 = \sqrt{2\pi\lambda R} \approx 10^3$ km, where λ is the wavelength, and R is the distance to the transition region, in the order of one hundred Jupiter's radii, $R \approx 100\ R_J$.

So, we can consider for the DAM the three layers propagation model with the first layer of weak phase fluctuations and the two other of strong and moderate fluctuations. In case of opposition and quiet nighttime ionosphere the characteristic scintillation frequency for the first layer is much higher than for the others. According to [Alimov et al., 1997] calculations of scintillation spectra results in

$$S_I(\Omega) = \frac{1}{\pi}\int_0^\infty \Gamma_I(\tau)\cos(\Omega\tau)\mathrm{d}\tau \approx \langle I \rangle^2 [2\langle s_1^2 \rangle] F_{N_1}(\Omega) + S_I^{'}(\Omega)],$$

where $\langle I \rangle$ is the mean intensity of received emission, $F_{N_1}(\Omega)$ is the one–dimensional spectrum of electron density fluctuations in the first layer, and $S_I^{'}(\Omega)$ is the normalized fluctuation spectrum of emission intensity scattered off the second and third layers. Furthermore, the fluctuation spectrum $S_I^{'}(\Omega)$ is determined by ionospheric scintillations only if $\nu_2 < \nu_3$. So, even weak fluctuations in the Jovian transition region can be detected if they are separated from the strong interplanetary and ionospheric ones having a higher characteristic scintillation frequency as in the considered case of Jupiter's opposition and quiet nighttime ionosphere.

3 Experimental results

A possibility of separation of the DAM scintillations between the transition region between the Jovian magnetosphere and the Solar wind from the ionospheric and interplanetary scintillations during Jupiter's opposition was tested experimentally using the ground–based SURA decametric radio telescope described in details in Karashtin et al. [1999]. Briefly, the SURA radio telescope has 300×300 m^2 antenna area divided along the north–south direction into three independent sub–arrays of 100×300 m^2 each. It can be operated in the frequency range of 4.7–9.3 MHz using circular polarization, both "O" and "X" switchable. The antenna main lobe can be inclined up to $\pm 40°$ from the vertical in the south–north direction. Two receiving systems were used in the described experiments: a short base (100 or 200 m bases) interferometer that uses distinct antenna sub–arrays, and a wide–band (up to 500 kHz) receiver with a quadrature detector. Both systems were used simultaneously. The interferometer provides an improved signal to noise ratio relative to the spatially decorrelated background such as cosmic and industrial noise while the wide–band receiver data can be used to exclude the interference from radio stations and to obtain a high temporal resolution.

Experiments were carried out in two campaigns in the end of September–beginning of October, 2000, (far from opposition, strong IPS should present) and in the end of November, 2000 (near Sun–Earth–Jupiter opposition). DAM emission was observed and recorded in both campaigns at frequencies about 8.9 MHz. An example of data obtained using the interferometer is shown in Figure 1 for October 07, 2000, in terms of antenna temperature versus local time that is LT = UT + 3^h. DAM was observed around $4^h 20^m$ and 5^h. An example data obtained using the wide–band receiver is shown in Figure 2. These data resulted from some preliminary processing of primary data obtained on November 23, 2000, using a receiver filter bandwidth of 20 kHz. Radio station interference was excluded using Fourier transformation and median spectral averaging. The intensity of the received emission is shown in Figure 2 in arbitrary units, DAM scintillations on the ionospheric irregularities can be clearly seen. The thick line in Figure 2 is the normalization curve obtained by low–pass filtering of the original data.

The obtained data were processed to obtain normalized scintillation spectra. First, the data were normalized using normalization curves like shown in Figure 2 and obtained by low–pass filtering of data. We are interested in the high frequency features of the scintillation spectra, and one of the substantial high frequency contributions is produced by lightning discharges of thunderstorms from moderate distance (up to a couple of thousand kilometers) that can be seen as sharp peaks of high intensity in Figure 2. The data were cleaned up from such kind of interference using the temporal derivative of intensity as an appropriate criterium. A comparison of normalized intensity before and after cleaning is shown in Figure 3. An absence of most intense short pulses in the cleaned data is evident, but some weak sharp pulses are still present and cannot be excluded by the algorithm used. Nevertheless, an essential increasing of sensitivity at high scintillation frequencies was obtained.

Scintillation spectra were derived from both cleaned and non–cleaned data. The obtained spectra for November 23, 2000, are compared in Figure 4. The low frequency parts of

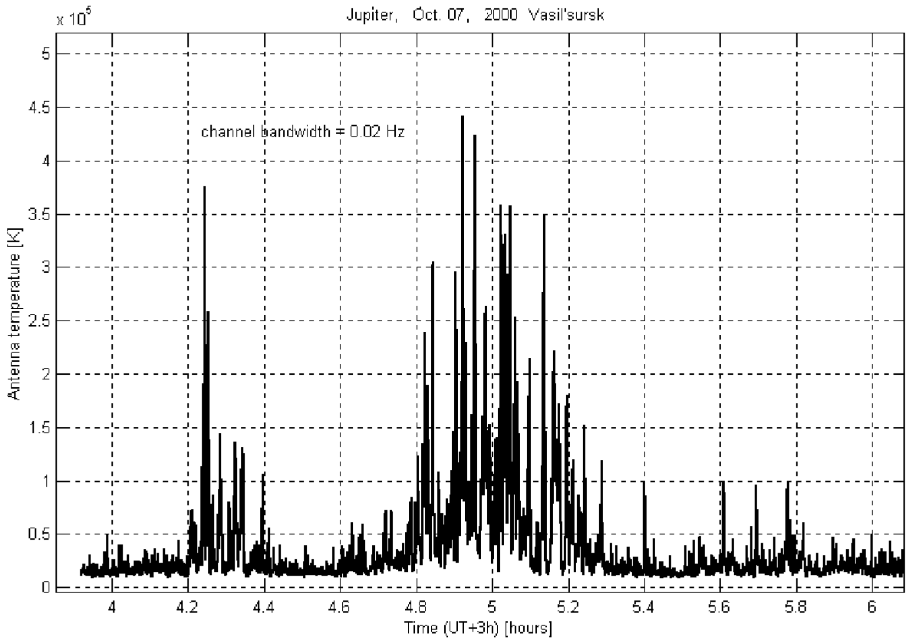


Figure 1: An example of DAM emission recorded at SURA by interferometer with 200 m base.

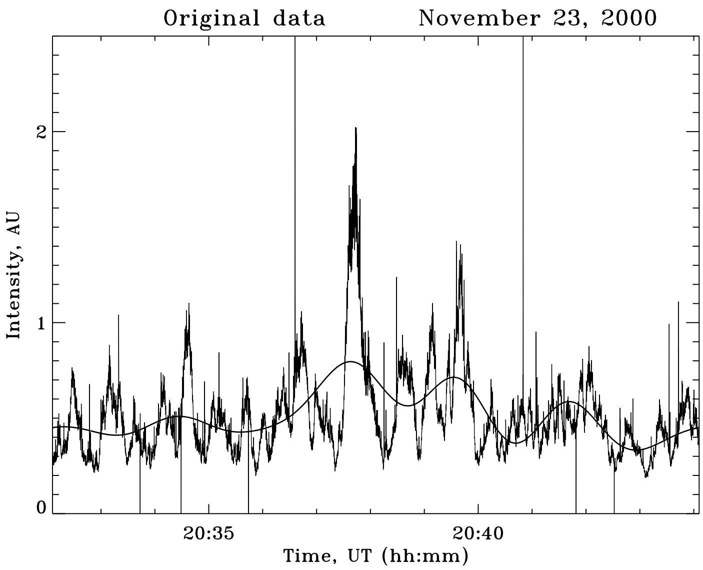


Figure 2: An example of DAM emission recorded at SURA by wide–band receiver (after preliminary processing). The thick line is a normalization curve obtained by low pass filtering.

both spectra are identical and corresponds to ionospheric scattering. The high frequency parts differ approximately by one order, decreasing for cleaned data. Therefore, lightnings are responsible for the high frequency part of the spectrum obtained from non–cleaned

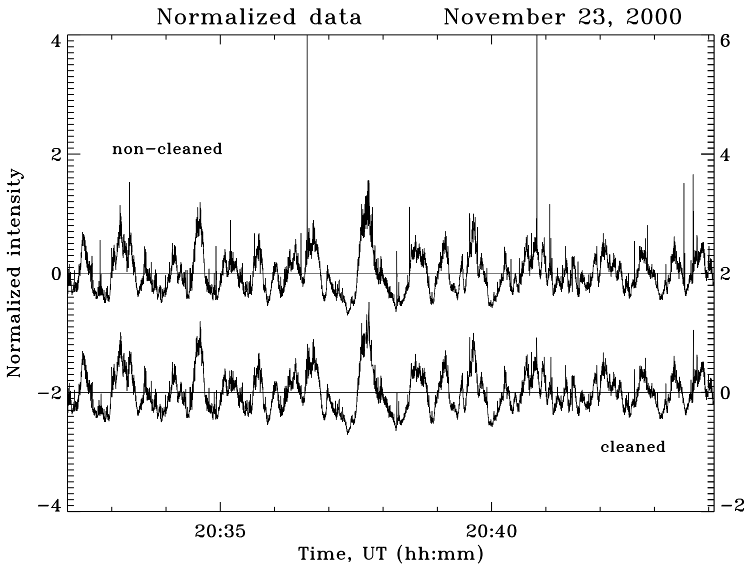
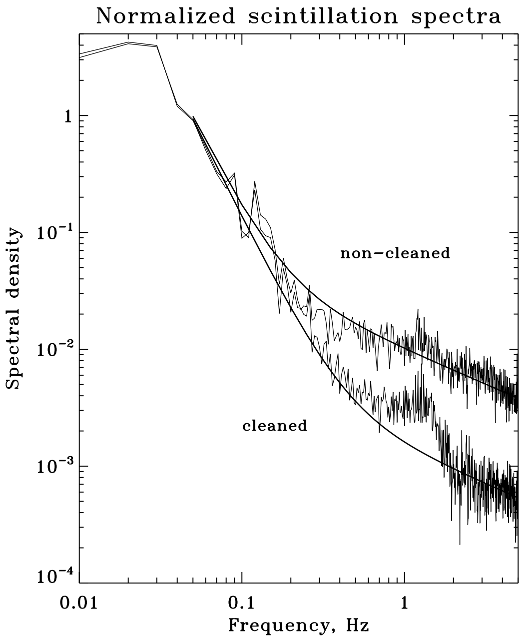


Figure 3: Normalized DAM records before (upper curve) and after (lower curve) cleaning from lightning discharges.

data showing clear power behavior $\propto \nu^{-0.6}$. The modeled spectra consisted of typical ionospheric low frequency scintillations [Alimov et al., 1997], and the power law contribution from lightning discharges are shown in Figure 4 by thick lines. The non–cleaned data spectrum is approximated by the modeled one quite well. As it can be seen from Figure 3, some weak sharp short pulses cannot be cleaned up from the data by the used cleaning technique. They correspond to weaker or more distant lightnings. If there are no other components in the scintillation spectrum obtained from the cleaned data, it should consists of ionospheric scintillations, the very same as for non–cleaned data, and reduced contribution from weak lightnings that was not cleaned up from the data. But comparing of observed and modeled spectra shows a definite coverage in the observed spectrum in the frequency range around 1 Hz.

Let us remind that the Figure 4 spectra were calculated from the data obtained during Jupiter's opposition (the end of November, 2000) when interplanetary scintillations should have a low characteristic frequency and should be masked by ionospheric scattering. Actually, comparing the Figure 5 spectra obtained during opposition on November 23, 2000, (Solar elongation about 180°) and far from it on September 30, 2000, one can see a dramatic difference between them. The characteristic frequency of the opposition spectrum is below 0.1 Hz while the spectrum obtained far from opposition is much wider. This difference can be explained by the dependence of interplanetary scattering on the angle between Solar wind velocity and the direction of wave propagation (see above section and Yakovlev [1998]).

As it was shown in the previous section, information on Jupiter's magnetosheath could be contained only in the data obtained under $\sim 180°$ Solar elongation conditions in the end of November, in the high frequency part (about 1 Hz) of the scintillation spectrum.



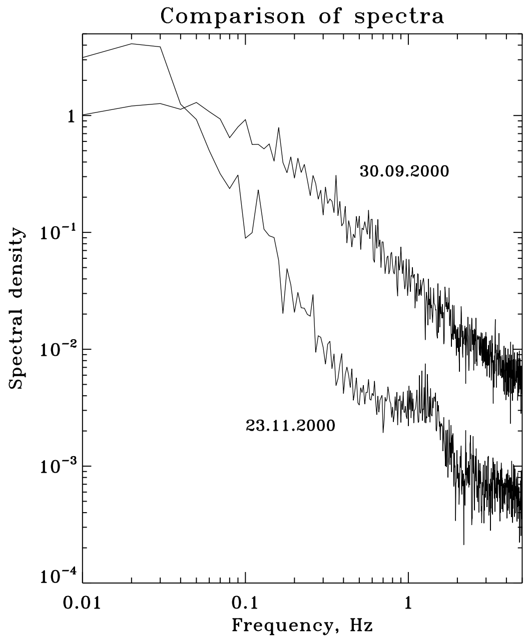


Figure 4: Left: DAM scintillation spectra obtained from cleaned (lower curve) and non–cleaned (upper curve) data. Thick lines correspond to modeled spectra consisting of ionospheric scintillations and contributions from lightnings.

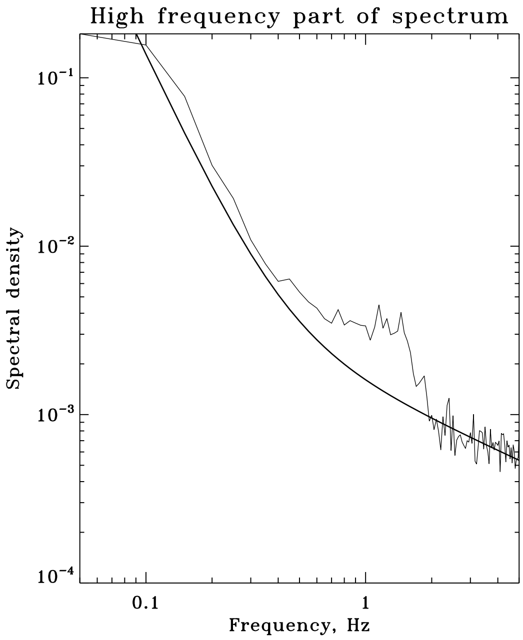
Figure 5: Right: Comparison of DAM scintillation spectra for opposition (November 23 (23.11), 2000) and non–opposition (September 30 (30.09.), 2000) conditions.

This part of spectrum (cleaned data) is shown in Figure 6 together with a modeled spectrum consisting of ionospheric scintillations and lightning discharges contribution shown as a thick line. The difference between observed and modeled spectra is shown in Figure 7. It is likely that this difference is caused by scattering of Jovian radio emission off irregularities in the transition region between Jupiter's magnetosphere and its bow shock. The scintillation index can be estimated from Figure 7 as $m = 3 \cdot 10^{-3}$.

4 Conclusion

Observations of DAM carried out in different geometry conditions of Jupiter's opposition and far from it showed that according to theoretical prediction, interplanetary scattering has an essentially narrower scintillation spectrum during opposition than far from it. This gives a possibility to investigate the weak scattering of Jupiter's emission off irregularities of transition region between the Jovian magnetopause and the bow shock. It was found from observations that in case of opposition the scintillation spectrum has a feature with a scintillation index of about $m = 3 \cdot 10^{-3}$ that is likely to correspond to such scattering.

Let us estimate the electron density fluctuations that could be responsible for the observed values. The index of weak scintillations can be estimated using the following approxima-



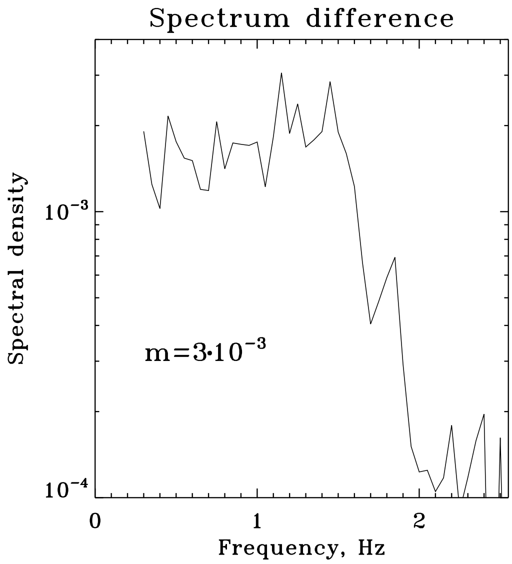


Figure 6: Left: High part of DAM scintillation spectrum obtained during opposition on November 23, 2000. Thick line corresponds to modeled spectrum.

Figure 7: Right: Difference between high frequency parts of observed on November 23, 2000, DAM spectrum and modeled one.

tion formula:

$$m \approx \frac{\omega_0^4}{\omega^2 c^2} \langle \left(\frac{\Delta N}{N} \right)^2 \rangle \ell_{eff} \Delta R$$

Here $\omega_0^2 \approx 3.2 \cdot 10^9 \langle N \rangle$ is the square plasma frequency of irregular layer with a mean electron density $\langle N \rangle$ (cm^{-3}), ΔR is the length of the layer, $\ell_{eff} = \sqrt{2\pi\lambda R}$ is the Fresnel scale (λ is wavelength, R the effective distance to the scattering layer), $\langle (\Delta N/N)^2 \rangle$ is the mean square of the relative electron density fluctuations in the scattering layer, c is the light velocity.

In our case observations were carried out at frequency of about $f \approx 9$ MHz ($\lambda \approx 3 \cdot 10^{-2}$ km) and $R \approx 90\ R_J \approx 7 \cdot 10^5$ km (R_J is the radius of Jupiter) that results in $\ell_{eff} \approx 10^3$ km. Supposing the thickness of Jupiter's transition region to be $\Delta R \approx 10\ R_J$ and the mean plasma density in it $\langle N \rangle \approx 1\ \mathrm{cm}^{-3}$, one can derive from the above formula that the obtained scintillation index $m = 3 \cdot 10^{-3}$ is correspondent to $\sqrt{\langle (\Delta N/N)^2 \rangle} \approx 10^{-2}$. Therefore, the observed fast scintillations of Jupiter's decametric emission could be caused by inhomogeneities in the "thin" layer of about 10 Jupiter's radii between the Jovian magnetopause and the bow shock with a characteristic scale of about 1000 km and relative electron density fluctuations of about 1 %.

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